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SIMULATED SPACE ENVIRONMENT TEST OF A 25-CELL CADMIUM SULFIDE THIN-FILM SOLAR-CELL MODULE

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16. Abstract

A 25-cell cadmium sulfide thin-film solar-cell module was tested in a simulated space environment for almost 2000 hours to determine the integrity of its mechanical and electrical connections and learn something of module electrical characteristics. During the test, the module was mechanically and electrically loaded to simulate spacecraft applications. There was no detectable evidence of degradation in the cell-to-cell connections. Maximum power output, fill factor, short-circuit current, and open-circuit voltage degraded in a manner characteristic of cadmium sulfide solar cells.

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SUMMARY

A 25-cell cadmium sulfide thin-film solar-cell module was tested in a simulated space environment for almost 2000 hours to determine the integrity of its mechanical and electrical connections and to learn something of its electrical characteristics.

Cells manufactured in 1967 and having unmatched electrical performance characteristics were used in the module, which was constructed using a reinforced solder technique. The module consists of five rows of cells connected in series. Each row of cells consists of five cells connected in parallel. During the test, the module was mechanically and electrically loaded to simulate spacecraft applications.

The test consisted of 1058 cycles of 1.5 hours each followed by 340 hours of constant illumination.

At the end of the test, there was no detectable evidence of degradation in the cell-to-cell connections. Electrical performance degradation was comparable to that of single cells manufactured in the same period and tested under similar cyclic conditions.

INTRODUCTION

Individual solar cells generate small amounts of power. In order to be used effectively as power generators in space, they must be connected together to form large areas of cells, or solar-cell arrays. Large-area solar-cell arrays have always been somewhat of a problem in that they must be stored on the spacecraft so as to withstand the rigors of launch and then be deployed in space.

The cadmium sulfide (CdS) thin-film solar cell is flexible and rugged, and so it need not be joined to a substrate for support or protection. When deployed in space, sheets of cells need only be put in tension to serve satisfactorily as an array.

As part of a CdS solar-cell development program, the Lewis Research Center contracted with the General Electric Company (ref. 1) to evaluate and develop methods of joining CdS cells into modules, the building blocks of arrays. After several different joining methods were devised and evaluated, a reinforced soldered joint and a conductive epoxy bonded joint were selected as the most promising and were subjected to a battery of tests. Included in these tests was a brief vacuum thermal cycling test to evaluate the mechanical integrity of four-cell modules. Both joining methods proved satisfactory and so four modules of 25 cells each were constructed by each method. These modules were constructed in late 1967 using cells manufactured in August and September (ref. 2). The emphasis in manufacturing the modules was placed on mechanical integrity. Therefore, the cells were not matched electrically, nor were they selected for their electrical performance.

Long-term testing in a space simulator was needed, however, to increase confidence in the integrity of the electrical and mechanical connections. Accordingly, a 25-cell thin-film CdS solar-cell module was tested with that as an objective. The test also provided an opportunity to determine qualitative electrical performance of the module with consideration given to the lack of selection and matching of cells. The test consisted of a cyclic portion followed directly by a short-term constant illumination portion.

MODULE AND TEST DESCRIPTION

A reinforced soldered module was tested. It is a five-cell by five-cell matrix of parallel- and series-connected cells (fig. 1). The cells were connected in parallel along each row to provide alternate current paths should an electrical connection fail. Figure 2 shows a cross-sectional view of the reinforced soldered joint. A complete description of the joint, its development, and module fabrication is given in the contractor's final report (ref. 1).

For space environment testing, the module was suspended from a glass-epoxy board frame by five pieces of Kapton tape. Figures 3 and 4 show the front and back of the module in the test fixture. To confirm joint stability, the module was suspended along one edge - its positive series connection edge. A uniformly distributed weight of 32.5 newtons per meter (2.25 lb/ft) was attached to the opposite end with loops of Kapton tape. This assured constant loading regardless of thermal forces on the module.

During testing, the module was connected to a fixed resistive load adjusted to the module maximum power determined during cycle 1. Module voltage was sensed at the center of the positive and negative tabs. Module current was taken through parallel leads attached about one-third of the way in from the end of each tab.

During module fabrication, the copper-clad Kapton paralleling strips were left protruding at the end of each row. For this test, the tabs were instrumented as a possible aid to analyzing module performance. As it turned out, however, no useful data resulted.

Before the module was placed in the vacuum tank, infrared photographs were taken of each cell with the module operated at a forward bias of 0.46 ampere. These photographs, called thermograms (ref. 3), showed hot spots in many of the cells. A similar set of thermograms was taken following testing.

A total of 20 thermocouples were attached to the back of the module. These were 40-gage welded copper-constantan thermocouples fastened to the back of the module with thermosetting adhesive Kapton tape. A small amount of a silicone heat sink compound was placed at the junction to ensure good thermal contact. Thermocouples were placed on selected hot spots, on selected parts of cell-to-cell connections, and on cells showing no thermal anomalies.

Temperature coefficients of maximum power and open-circuit voltage were taken at the beginning and end of the test. These coefficients were calculated from voltage-current (V-I) curves taken in the vacuum tank using the xenon solar simulator. A new technique was used to obtain these data. This was done because an ambient test facility large enough to measure the module was not available.

The module was first brought to operating temperature in the simulated environment. The light beam was then doused until module temperature dropped to about 10° C. The light-beam douser was then removed, and a series of V-I curves was taken as the module warmed up to operating temperature. The thermocouple located at the center of the module was considered representative of module temperature.

Vacuum levels during the test were maintained at 10^{-7} torr or better. Solar simulation was accomplished by a 12.6-kilowatt xenon compact-arc lamp solar simulator. Solar simulator intensity was monitored continuously at the test plane by four silicon solar cells. Figure 3 shows two silicon monitor cells. Two more were added at the opposite vacant corners after the photograph was taken. Cycle time was 1 hour of light and 1/2 hour of darkness.

A complete description of the facility, including calibration of uniformity and spectral distribution, is given in the appendix.

RESULTS AND DISCUSSION

The module was first exposed to 1058 light/dark cycles and then to 340 hours of continuous illumination with no interruption between types of testing. During testing, electrical measurements showed no indication of joint degradation. Following testing, a visual examination also revealed no joint degradation.

Losses in module performance as a result of simulated space environment during cyclic and continuous illumination testing are shown in figure 5 and summarized in table I. These data are for air mass zero (AM0) intensity and 50.7° C, the average module temperature during cycle 1. The results reported herein are comparable to results from tests of single cells manufactured in the same period and tested under comparable conditions (ref. 4).

In general, the module lost maximum power and fill factor quickly during the first 100 cycles and then at a gradual rate through the end of the test. Open-circuit voltage dropped slightly during the first 100 cycles and then remained steady through the end of the test while short-circuit current increased slightly during the first 300 cycles and then decayed slowly through the end of the test.

There were three instances during testing when the module recovered output power capability that may be related to perturbations in testing. The first was at cycle 275, when a breakdown in the vacuum system forced a 4-day interruption in testing. During this shutdown, the vacuum level reached the 10^{-3} torr range. The data shown at cycle 275 were taken in the first cycle following resumption of testing. Maximum power went from 83 percent at cycle 195 to 92.5 percent at cycle 275. Apparently, the long dark soak had a beneficial effect on the module.

There are reported cases of single cells recovering following dark storage after having been degraded under constant illumination and open-circuit conditions (ref. 5).

The second instance was at cycle 690. Data (V-I curves) were taken at cycle 672 and again at cycle 690. Between these data points, the solar simulator was shut down for 2 days for routine maintenance. In this instance, output power went from 79.7 percent before shutdown to 81.4 percent after shutdown. During the shutdown simulator optics were cleaned. It is impossible to say, therefore, whether the dark soak or the changed spectrum resulting from clean optics effected this power increase.

The third instance of output power recovery occurred during constant illumination testing. After 188 hours of continuous illumination, testing was interrupted for 4 days because of solar simulator problems. Data taken just prior to and immediately following the interruption show maximum power going from 74.8 percent before shutdown to 77.2 percent after shutdown. An error in resetting the controls following this interruption caused the system to operate in a cycling mode for 16 cycles. Data taken at the end of those 16 cycles showed maximum power increasing again, this time to 79.2 percent.

Three factors may have influenced these last changes in power: first, the long dark soak; second, cycling as opposed to constant illumination; and third, taking V-I curves 16 cycles apart. It has also been shown that individual cells recover some lost performance as a result of taking V-I curves (ref. 5).

The average module temperature was 50.7° C at cycle 1 and 55.9° C at the end of the test. The difference is most probably due to degraded optics in the solar simulator. Figure 6 is a front view of the module showing the locations of the thermocouples and the average temperature for each thermocouple. Three thermocouples failed to record properly and were not included in the average. Another thermocouple, located on an intense hot spot, showed that the temperature of that portion of the cell would increase as much as 15° C when a V-I curve was taken. The increase in temperature occurred when the module went from a loaded condition to open-circuit voltage at the start of a V-I curve. Following a V-I curve, the temperature at that thermocouple would slowly drift back to its initial V-I curve level. That thermocouple was also omitted from the average temperature calculation.

Comparing the before and after thermograms showed a net gain in hot spots. Based on other test results (ref. 5), the disappearance of initial hot spots and the formation of new spots in the manner observed is not unusual. Neither the intensity nor the number of new spots is believed to have affected the test results in any unusual manner. Although hot spots are considered to be directly related to changes in cell performance, their presence, appearance, and disappearance is at best only a qualitative measure of cell stability.

The temperature coefficients of maximum power and open-circuit voltage taken at the beginning and end of the test are listed in table II. These data, when reduced to a per-cell basis, compare favorably with individual cell coefficients. The change in the coefficients is typical of what is observed for individual cells.

CONCLUDING REMARKS

A 25-cell CdS solar cell module mechanically loaded at 32.5 newtons per meter (2.25 lb/ft) shows no joint deterioration after simulated space environment testing. The electrical performance of the module during cycling was in all respects similar to that of single cells manufactured in the same period and tested under similar cyclic conditions. Based on the limited data obtained from this test, no additional problems are evident when CdS cells are operated in a matrix in a module.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 22, 1970,
120-33.

APPENDIX - 5-FOOT- (1.52-m-) DIAMETER

VACUUM THERMAL CYCLING FACILITY

Figure 7 shows the 5-foot- (1.52-m-) diameter vacuum tank and its associated solar simulator, and figure 8 describes some of the particulars of the system.

The 5- by 7.5-foot (1.52- by 2.25-m) vacuum chamber (fig. 8) has liquid-nitrogen-cooled walls capable of maintaining a vacuum of 1×10^{-8} torr and was used for this vacuum thermal cycling test. The liquid-nitrogen-cooled walls maintain solar-cell temperature at about 50° C when illuminated with AM0 simulated sunlight. With the solar simulator turned off, solar-cell temperature drops to -150° C in about 3 minutes.

A Spectrolab X-75 xenon lamp solar simulator is capable of maintaining an intensity of 1 solar constant at either the 21- by 21-inch (0.53- by 0.53-m) or 24- by 24-inch (0.61- by 0.61-m) test plane. For this test, the module was located at the 21- by 21-inch (0.53- by 0.53-m) test plane. The illumination uniformity in the 21- by 21-inch (0.53- by 0.53-m) test plane was mapped by using a specially constructed mapping device. This device consists of a silicon solar cell mounted in such a way that the cell can be moved in the horizontal and vertical directions in the test area. The intensity at the center of the mapping device was adjusted to the 1-solar-constant level. The uniformity was then mapped by manually moving the solar cell in a continuous scan in the horizontal (x) direction and in 2-inch (5.08-cm) step intervals in the vertical (y) direction. The output of the silicon cell was connected to an x-y recorder. The illumination uniformity over the test area was measured to be within ±3 percent of 1 solar constant.

The spectral output of the simulator is measured over the wavelength range of 250 to 1900 nanometers by a filter radiometer. This device consists of a series of 12 transmission filters and a thermopile detector to measure the radiation transmitted through each filter. The data obtained by the detector are then analyzed by means of an iterative computer program to obtain the spectral distribution of the simulator. The spectral distribution for the X-75 simulator compared to the Johnson curve for AM0 sunlight is shown in figure 9. The maximum differences between the simulator and the Johnson curve (30 percent and -9.4 percent) occur in the region between 0.25 and 0.46 micrometer.

Light intensity is continuously monitored during testing by four silicon solar cells mounted in the test plane and connected to a four-channel strip-chart recorder.

Cell temperatures are measured by 40-gage welded copper-constantan thermocouples attached to the cells by 1-centimeter-square pieces of Kapton tape. Cell temperatures are recorded on a 24-point temperature recorder.

Two silicon cells, attached to the module mounting frame, were used to trigger an elapsed-time clock that measures the amount of time the test sample is illuminated.

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TABLE I. - LOSSES IN MODULE PERFORMANCE DURING SIMULATED SPACE ENVIRONMENT TESTING

	Losses during cycling, percent	Additional losses during constant illumination, percent	Total losses, percent
Maximum power	22.0	1.7	23.7
Fill factor	17.3	+0.9	16.4
Open-circuit voltage	2.2	0	2.2
Short-circuit current	3.6	3.1	6.7

TABLE II. - MODULE POWER AND VOLTAGE TEMPERATURE COEFFICIENTS

Temperature coefficient	Before test		After test	
	Module	Per cell	Module	Per cell
Maximum power, mW/^{o}C	-29.45	-1.18	-31.3	-1.25
Open-circuit voltage mV/^{o}C	-8.74	-1.75	-6.25	-1.25

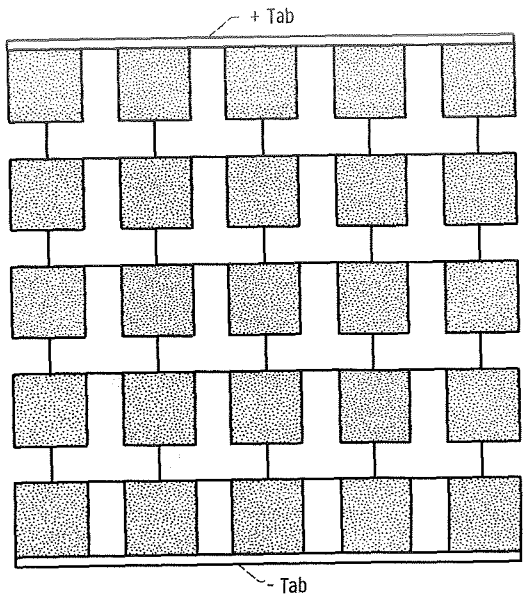

Figure 1. - Schematic drawing of 25-solar-cell module.

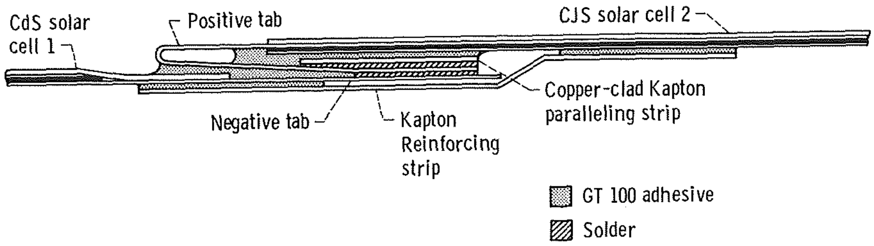

Figure 2. - Reinforced soldered joint.

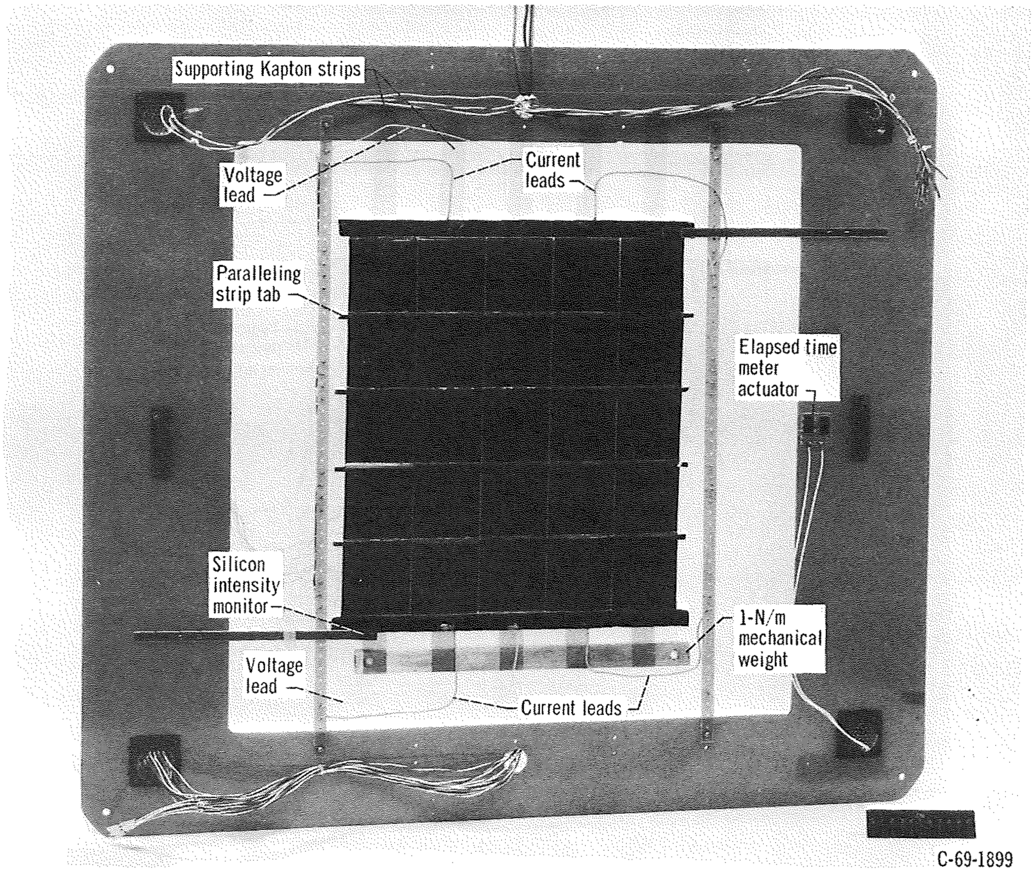

Figure 3. - Front view of module on test fixture.

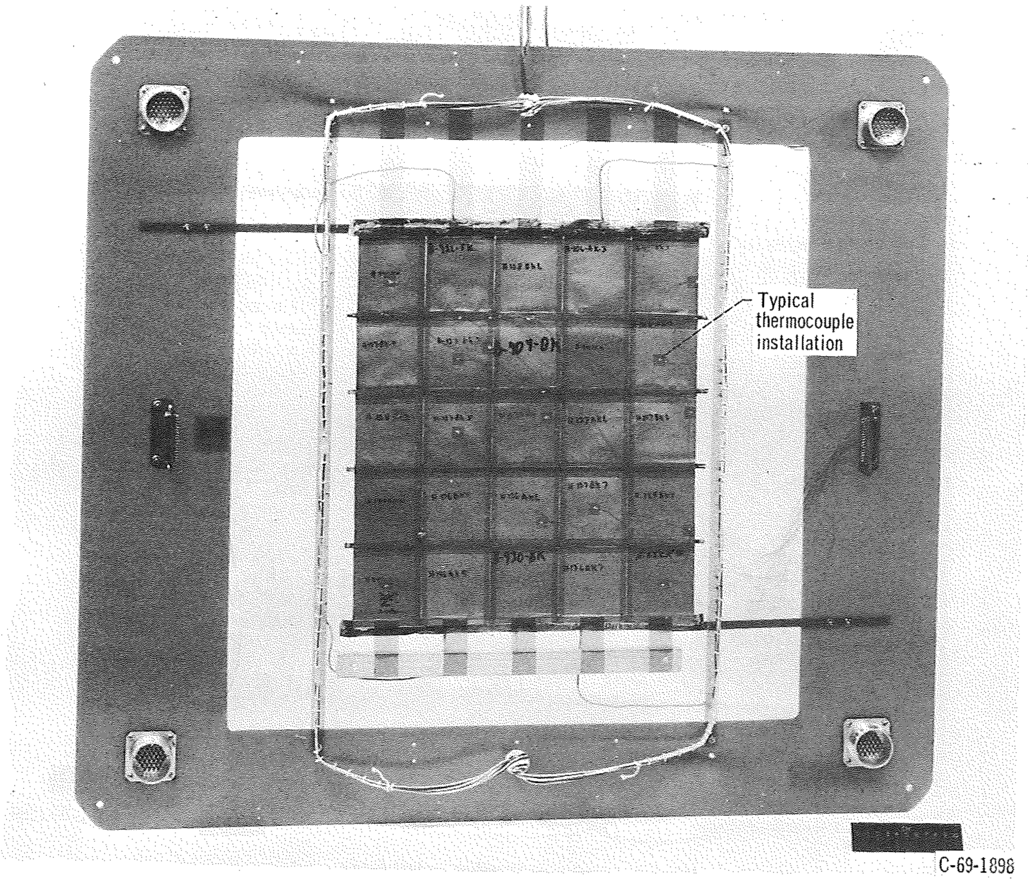

Figure 4. - Rear view of module in test fixture.

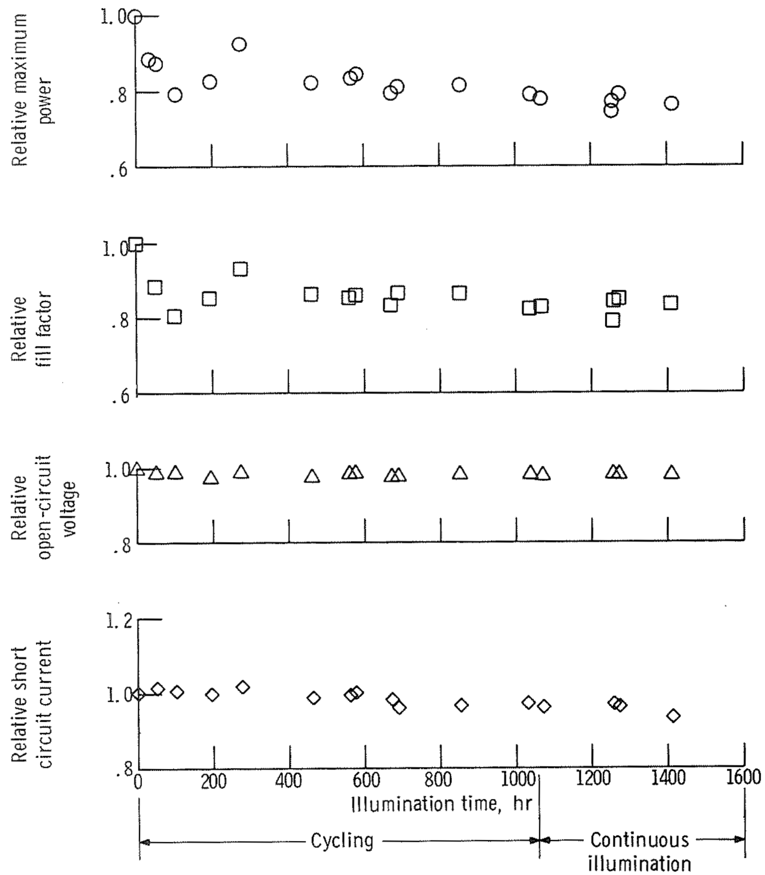

Figure 5. - Module performance during simulated space environment testing.

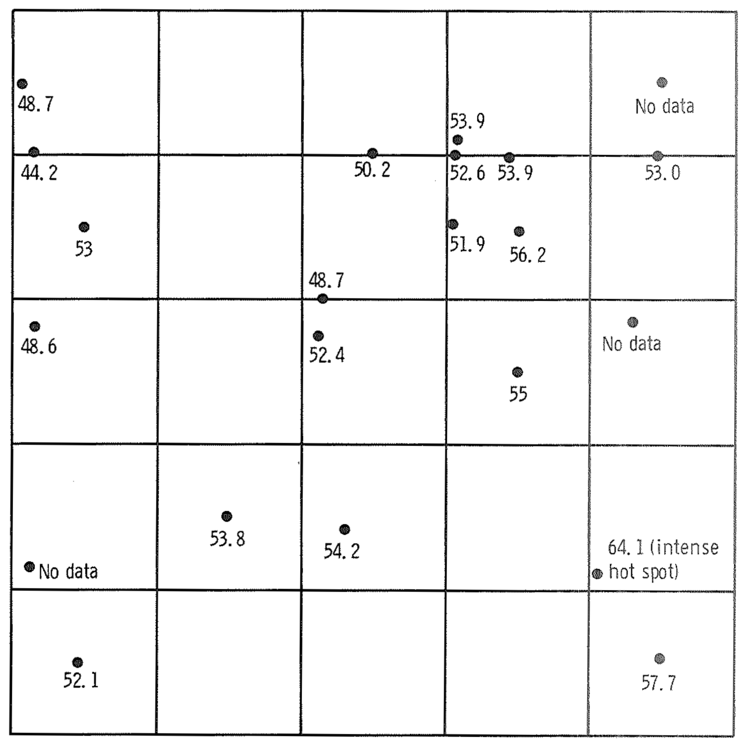

Figure 6. - Front view of module showing thermocouple locations and average temperatures (in °C).

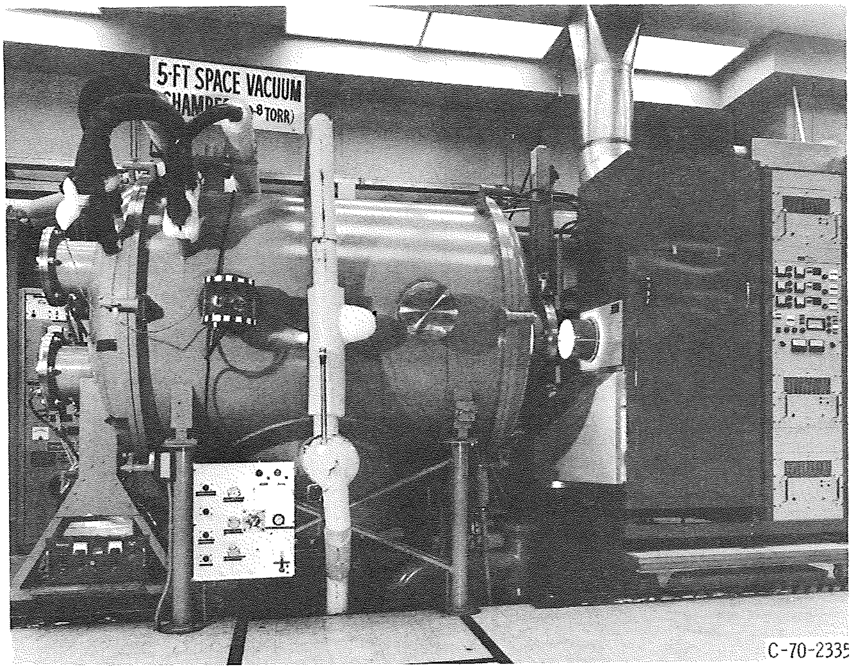

Figure 7. - 5-Foot- (1.52-m-) diameter vacuum tank and 12.6-kilowatt solar simulator.

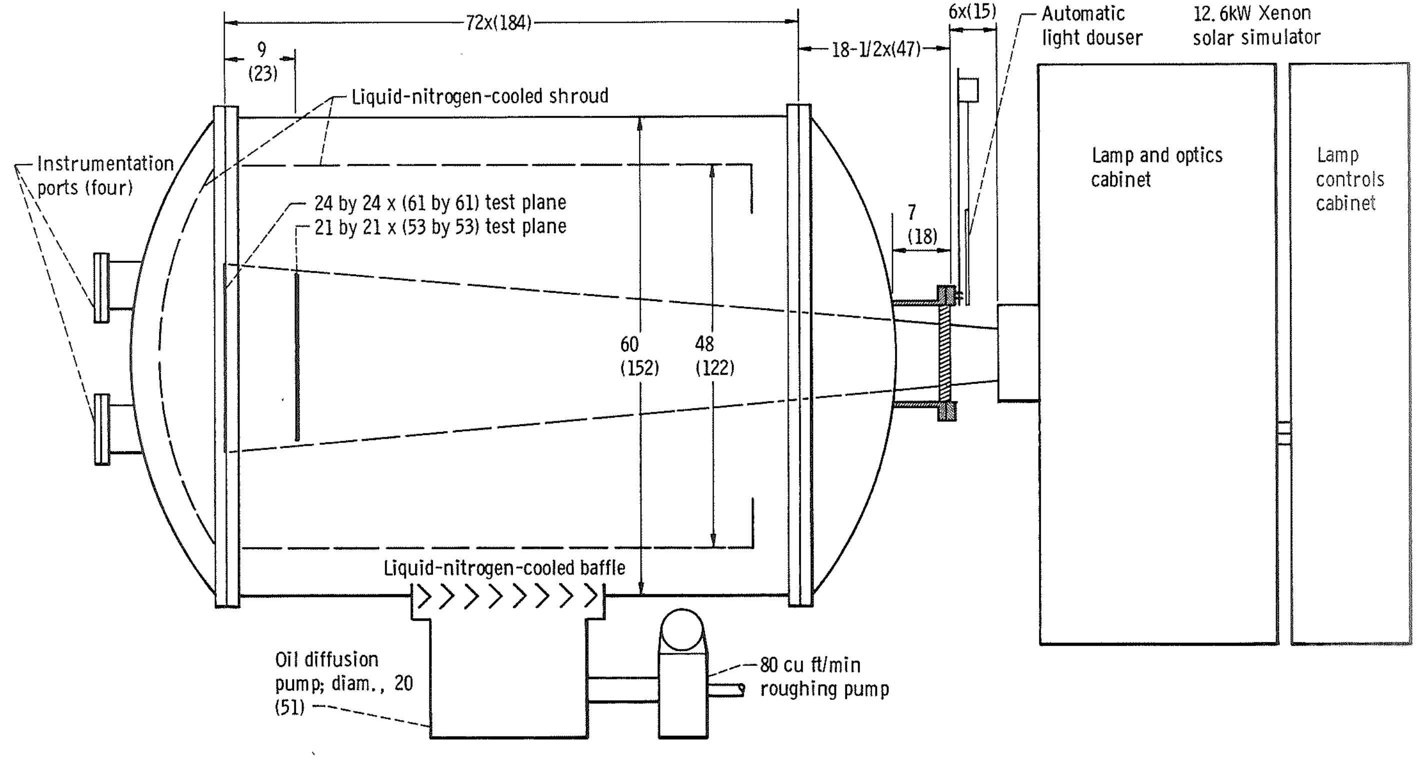

Figure 8. - Details of 5-foot-(1.52-m-) diameter vacuum tank and 12.6 kilowatt solar simulator. (Dimensions in inches (cm).)

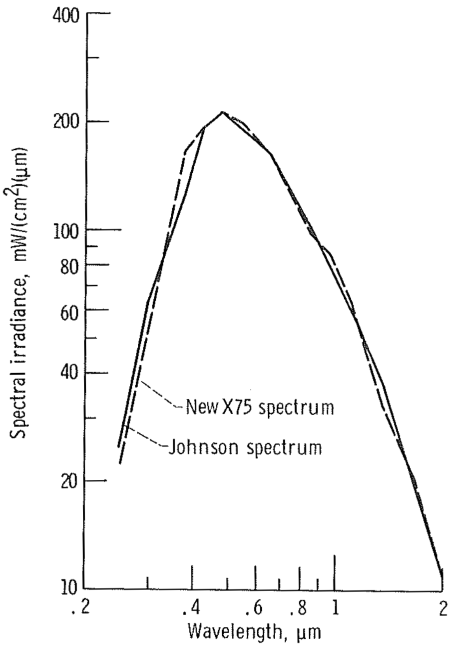

Figure 9. - Spectral irradiance of X-75 solar simulator normalized to 140 milliwatts per square centimeter and compared to AMO Johnson curve.

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